Contrail-Cirrus – Man-made Experiments on Complex Cloud Physics

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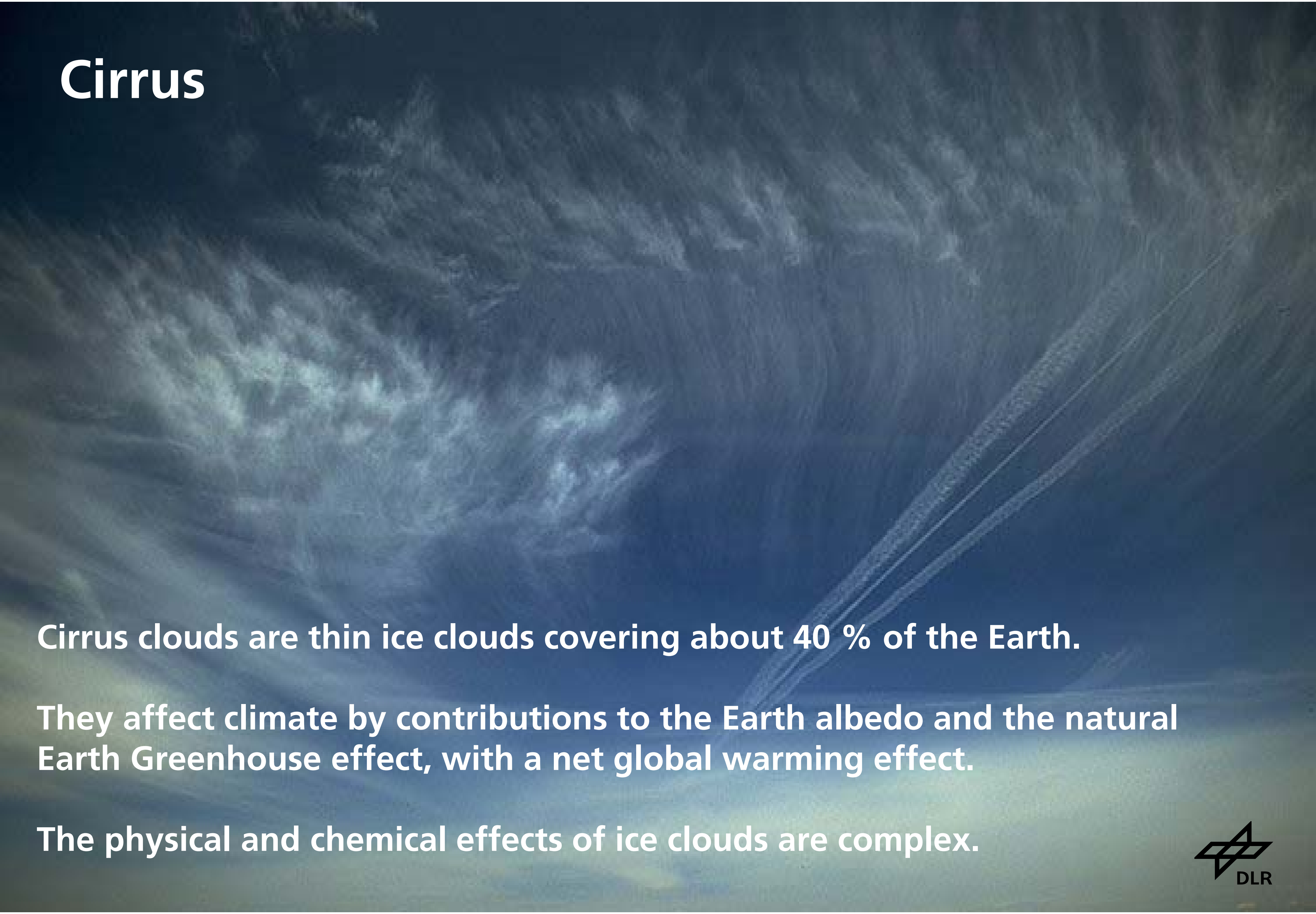
TOPICS:
- Cirrus
- Contrails
- Past: Brewer-Dobson, TIL, Ice Supersaturation, Nucleation
- Present: Contrail Prediction, Validation, Climate Impact
- Future: Mitigation

DLR


Cirrus
Cirrus clouds are thin ice clouds covering about 40 % of the Earth.
They affect climate by contributions to the Earth albedo and the natural Earth Greenhouse effect, with a net global warming effect.
The physical and chemical effects of ice clouds are complex.
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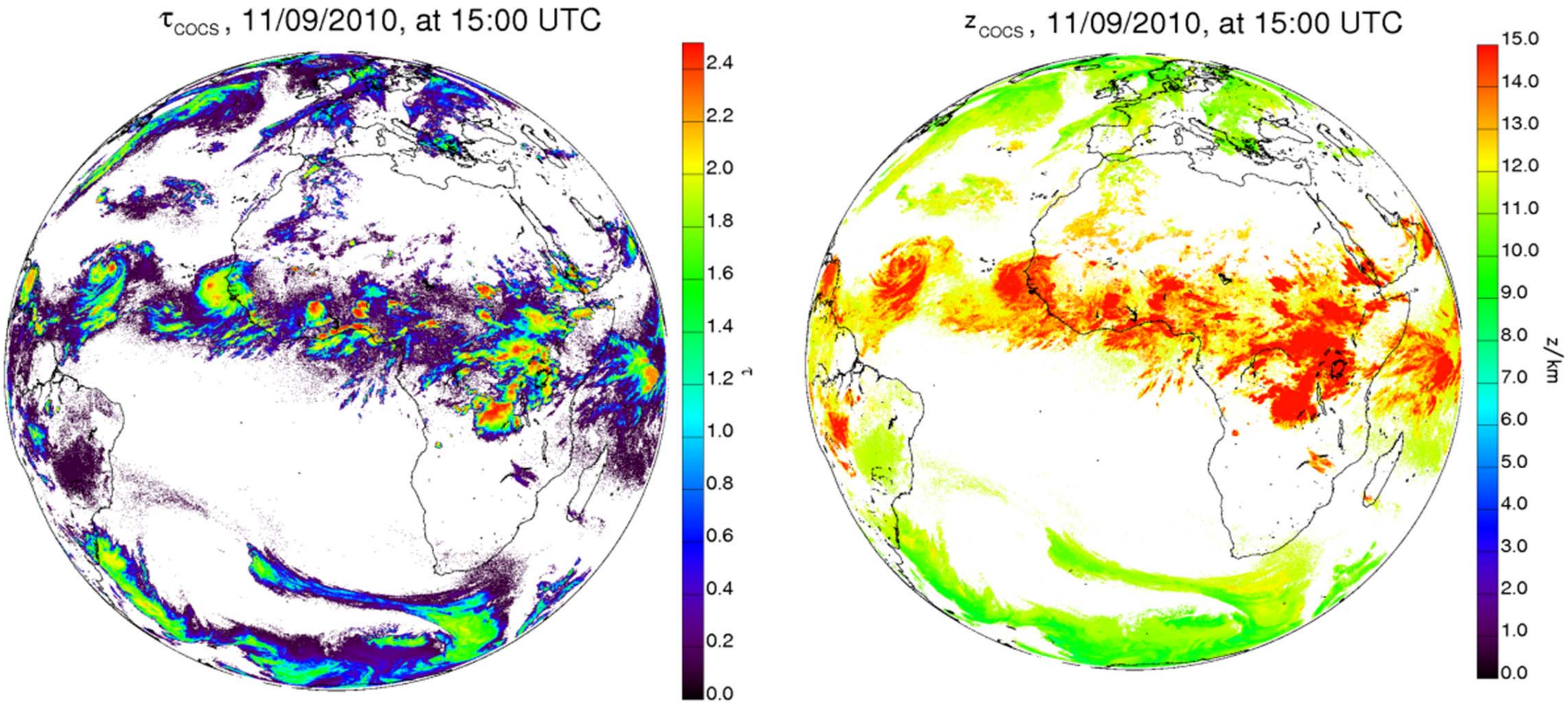
Cirrus Optical properties (optical depth and altitude) derived from Caliop and Seviri ("COCS")



(Kox et al., AMT, 2014)

Contrails

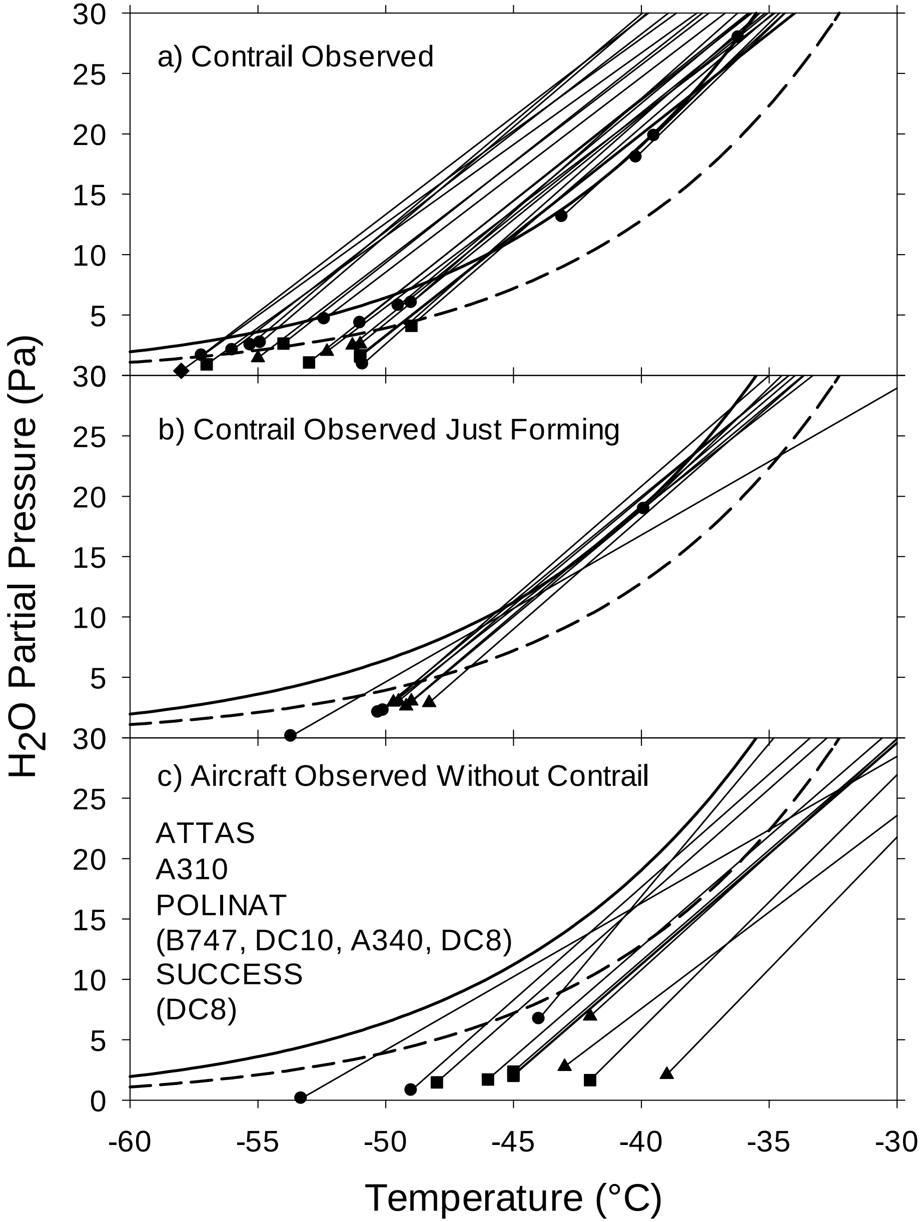
Contrails are a specific type of cirrus clouds induced in cool and humid air masses by aircraft.

Contrail cirrus contribute the largest and most uncertain part to the climate forcing from aviation.

Contrail formation is predictable and controllable to some extent.

Contrail cirrus formation can be interpreted as a man-made experiment in the atmosphere.

Contrail formation, requires liquid saturation -> water vapor condenses on soot-CCN and then freezes



(Schumann, 1996, 2000)

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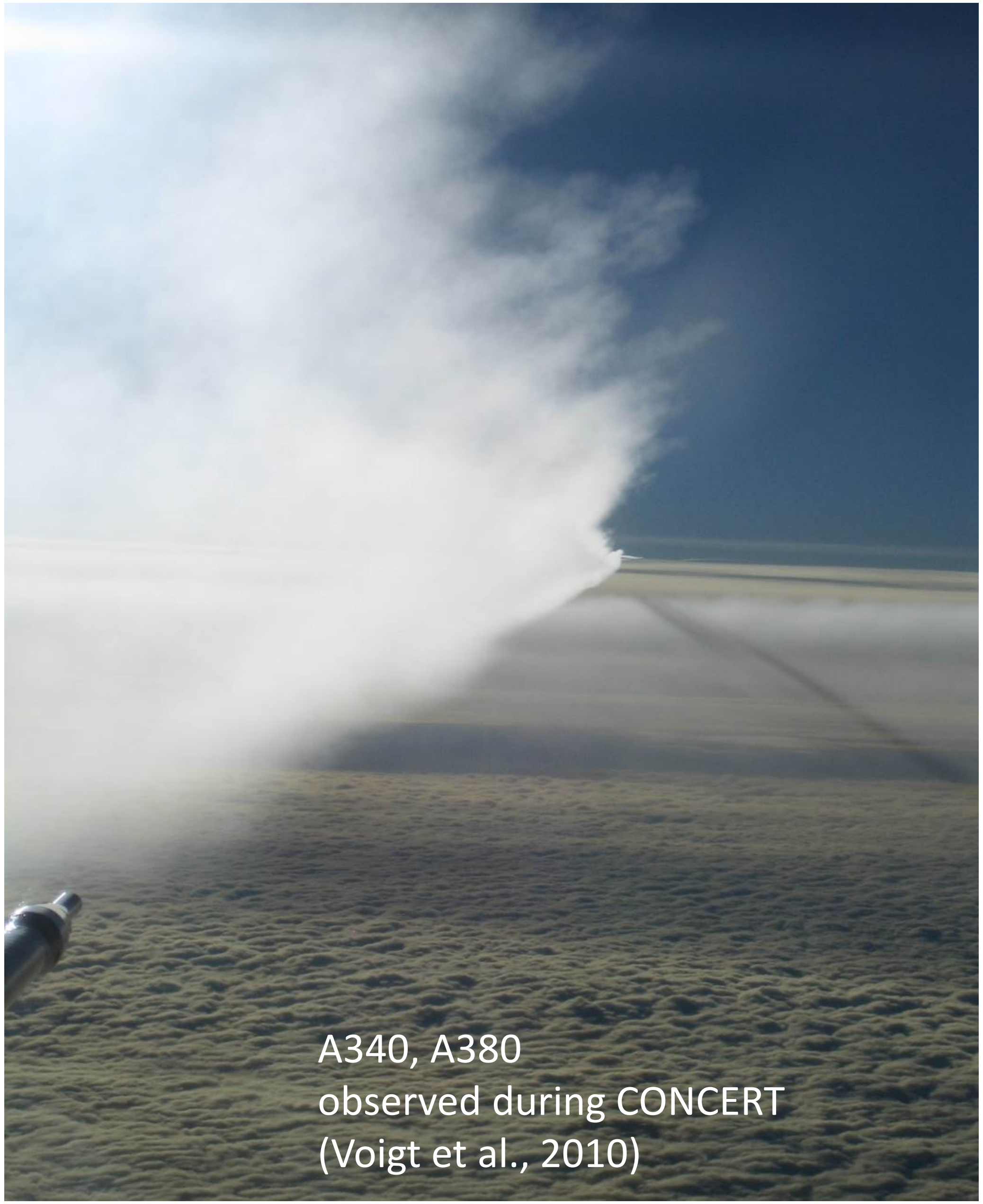
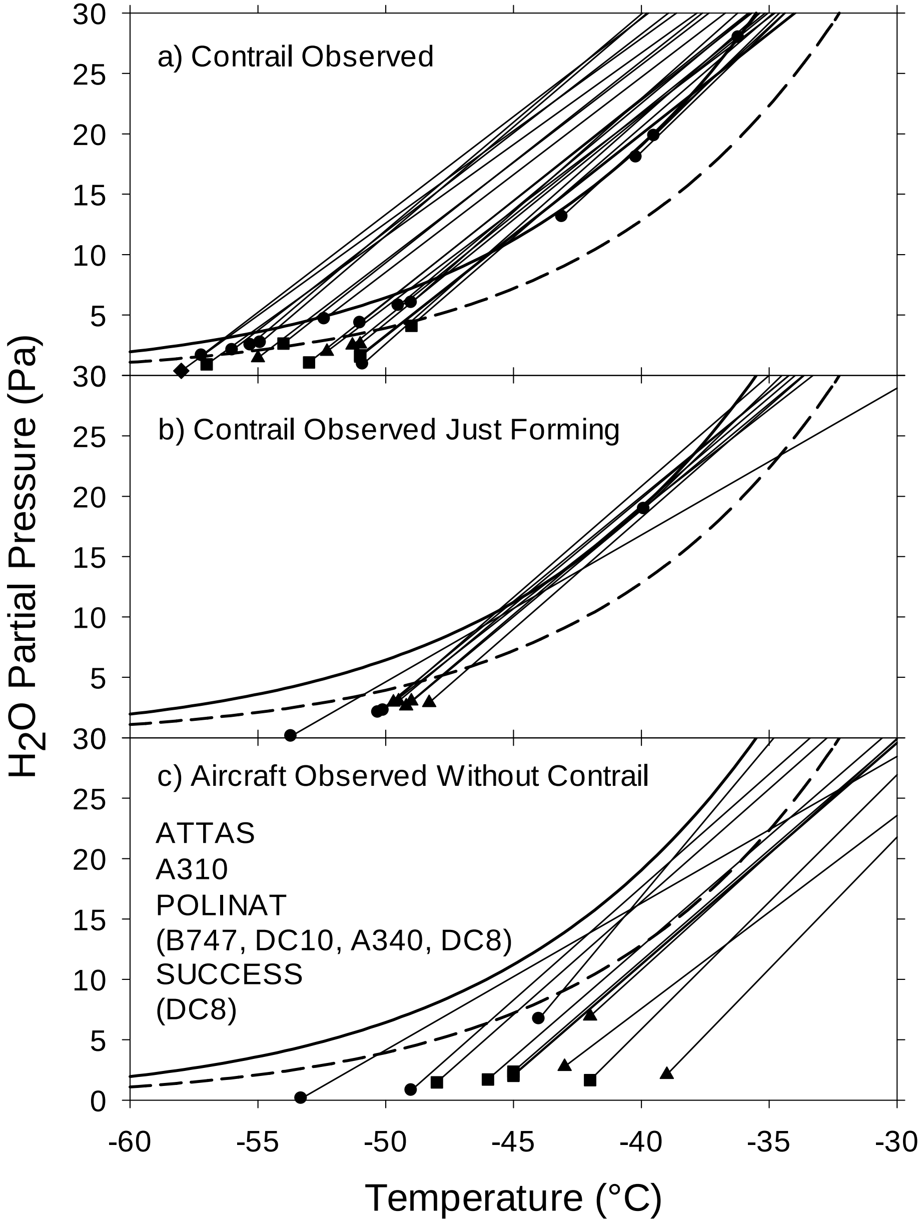
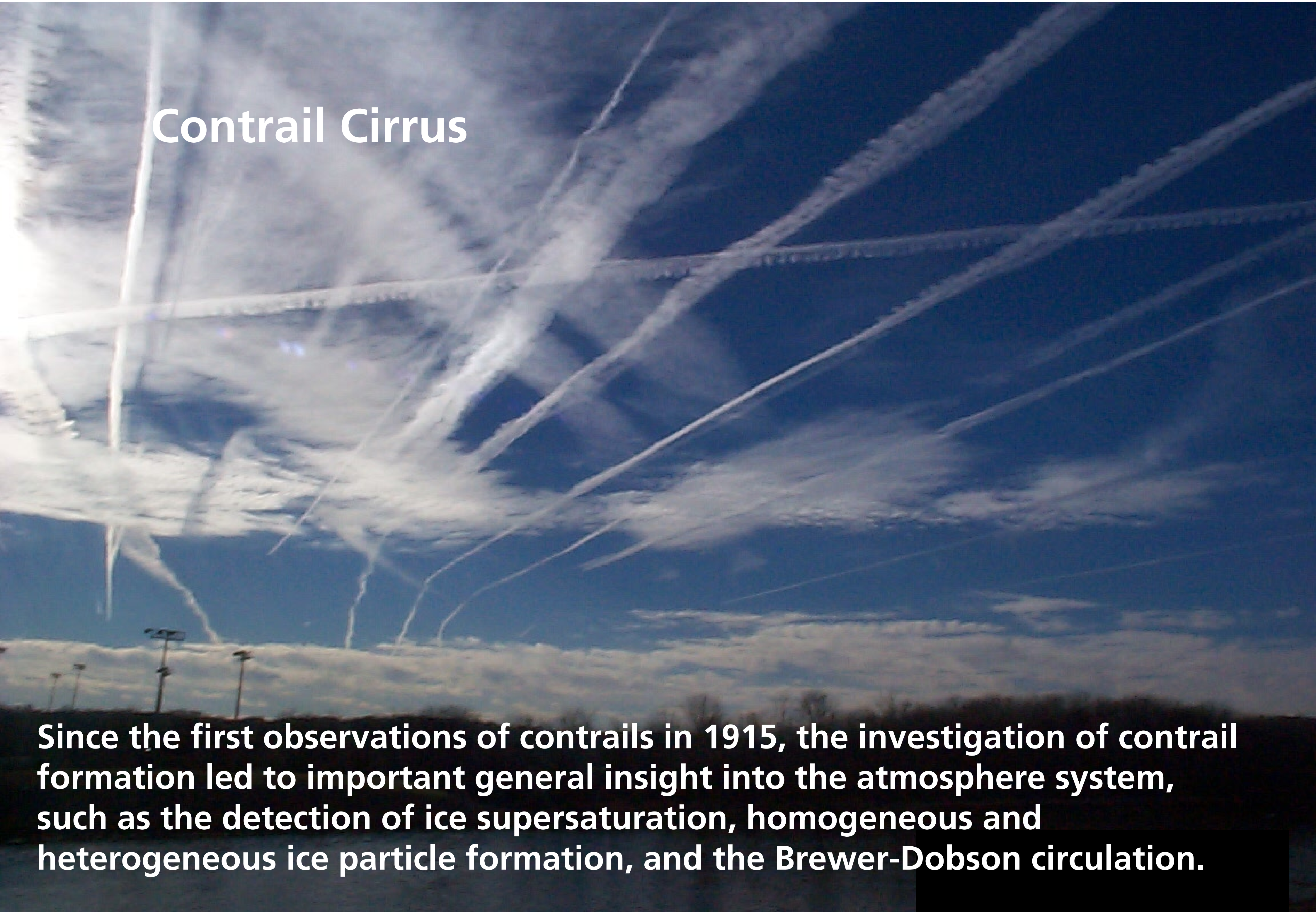




(Schumann, 1996, 2000)



Contrail Cirrus

Since the first observations of contrails in 1915, the investigation of contrail formation led to important general insight into the atmosphere system, such as the detection of ice supersaturation, homogeneous and heterogeneous ice particle formation, and the Brewer-Dobson circulation.

Discovering the Stratospheric Circulation

Brewer (1946, Bakerian Lecture): *frost-point profiles were measured to explain short contrails above tropopause → the stratosphere was found to be very dry.*

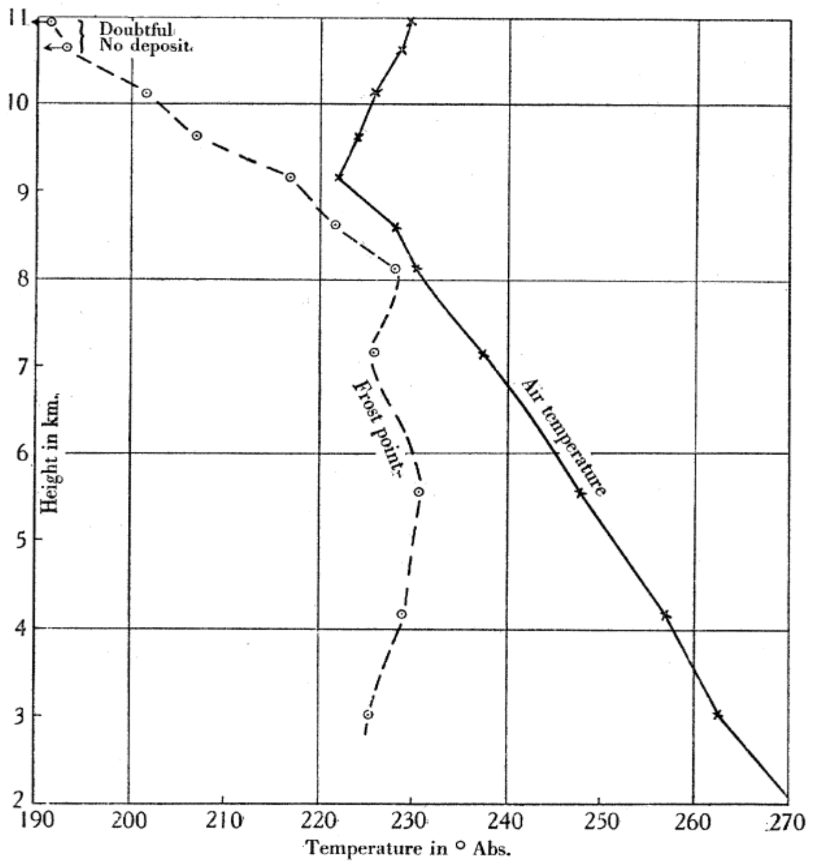
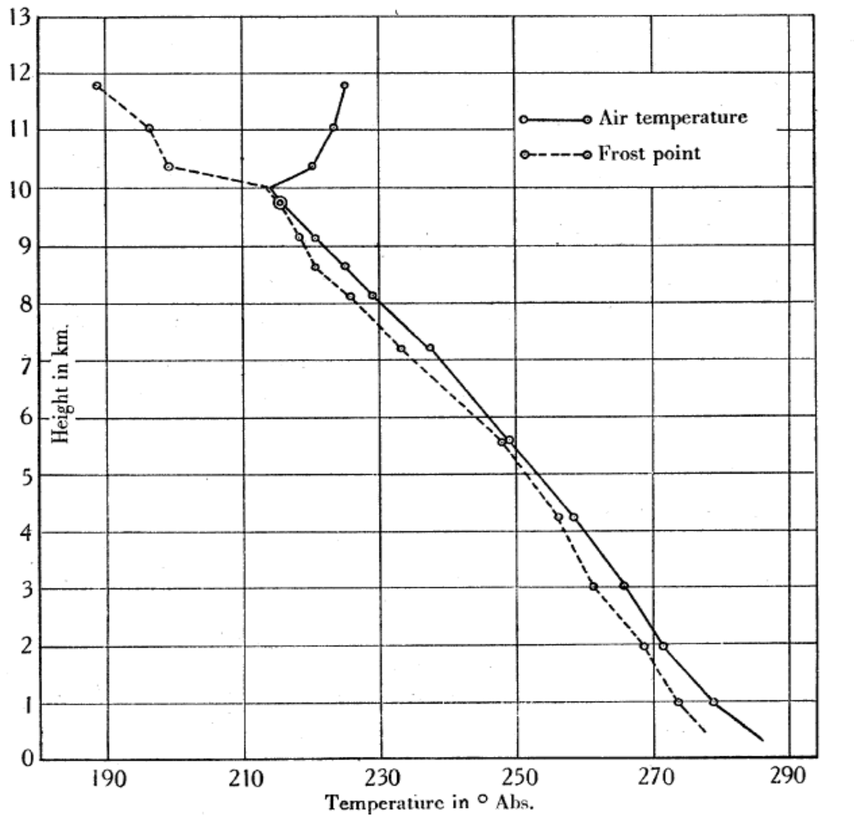


FIGURE 4. Frost-points and air temperatures observed on the first ascent when humidities were measured in the stratosphere, Boscombe Down, 22 December 1943.



rost-points and air temperatures observed on Boscombe Down, 30 May 1945, 0 G.M.T. The frost-point at the top is the lowest yet observed.

Discovering the Stratospheric Circulation

Brewer (1949): *"... dryness is maintained by a slow circulation of the air in which air rises at the equator moves poleward in the stratosphere and then descends into the troposphere in temperate and polar regions ..."*

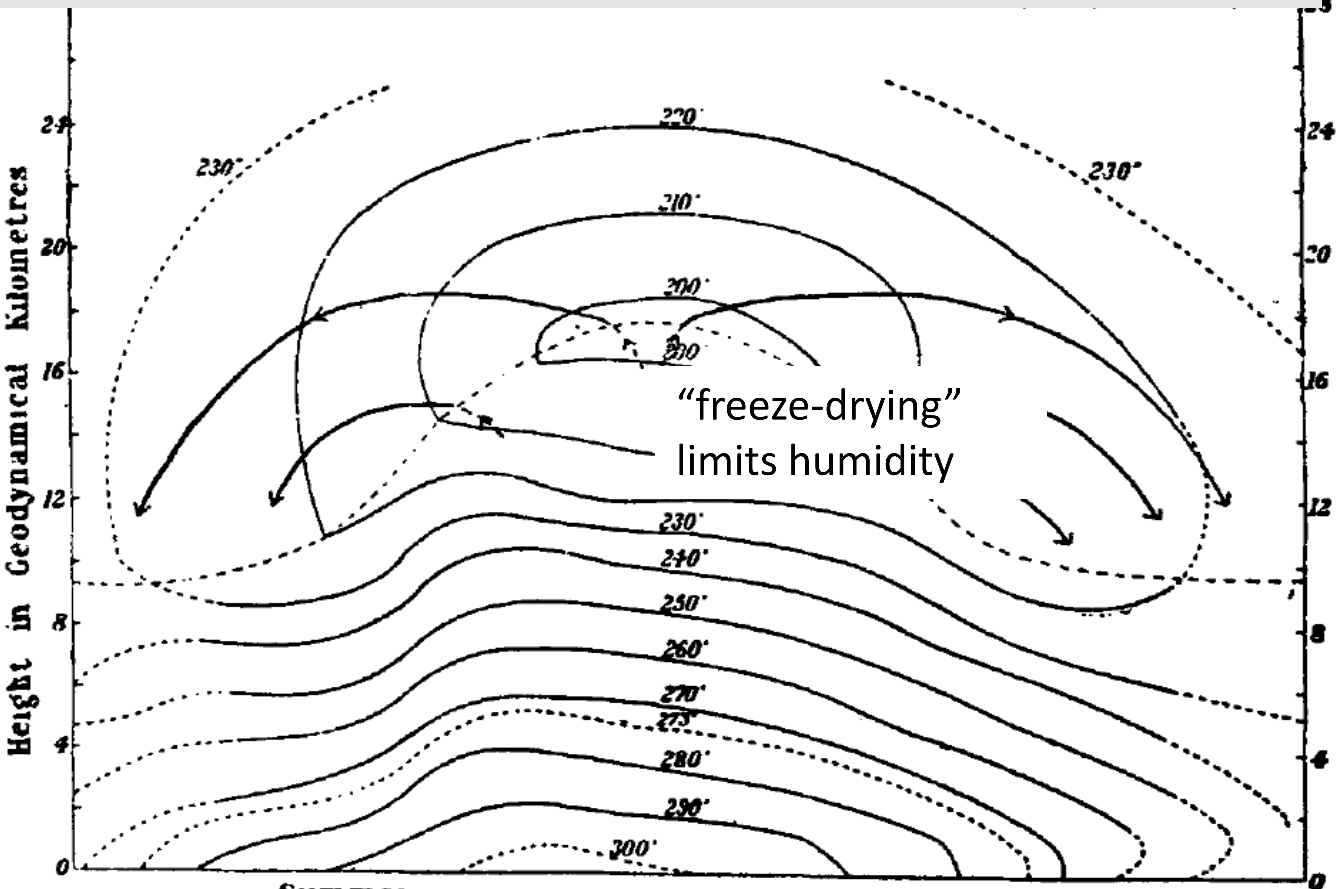


FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

Discovering the Stratospheric Circulation

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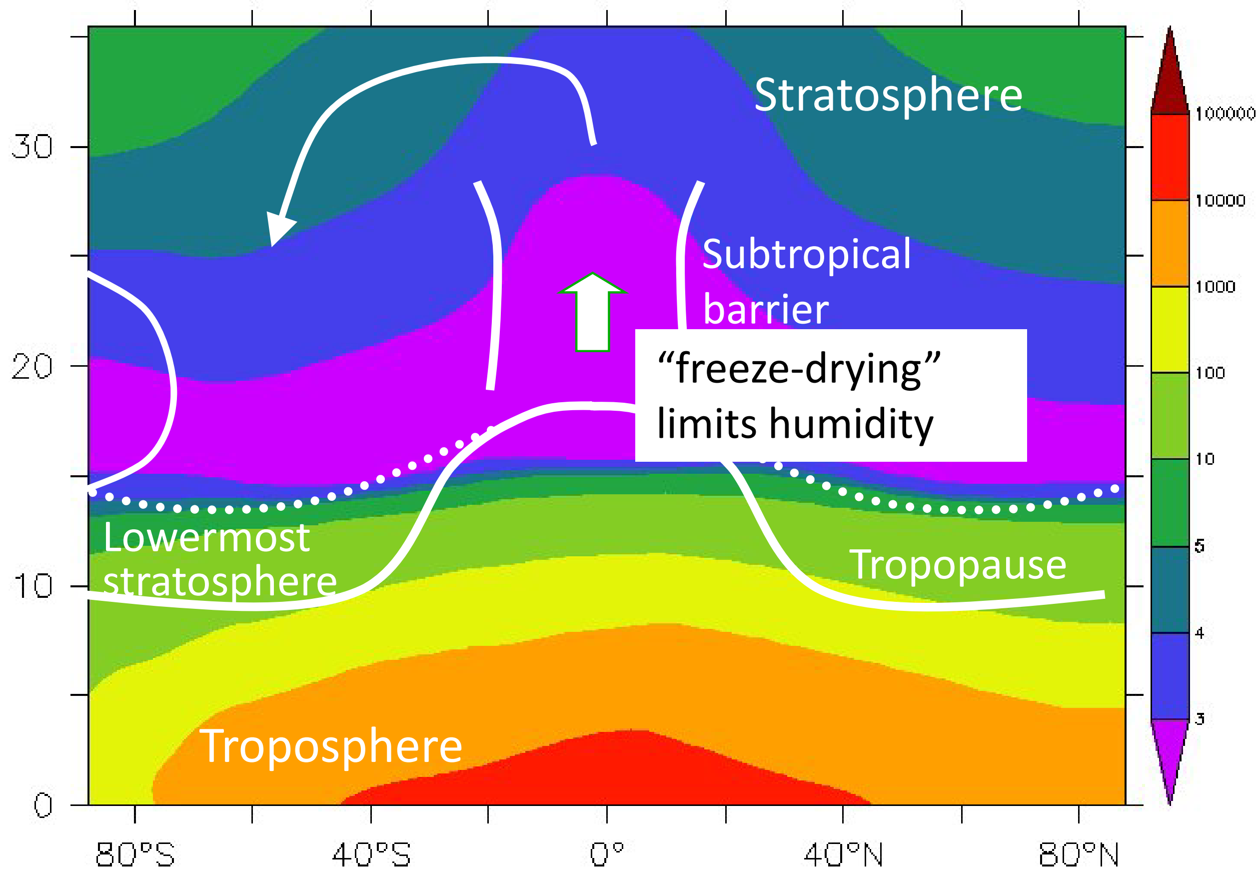
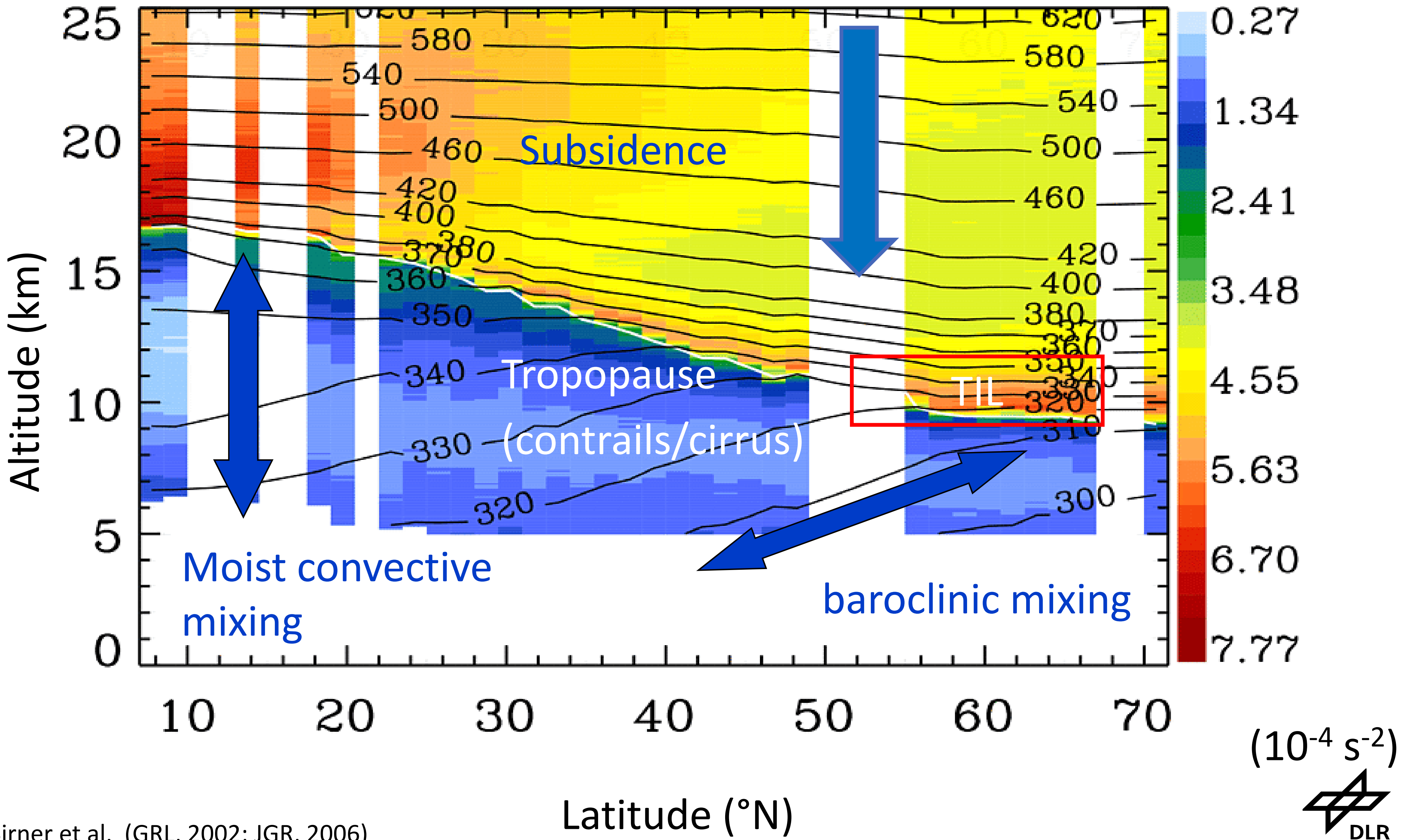


H_2O molar mixing ratio/(μmol mol^{-1})

September (from EMAC, courtesy Volker Grewe)

Tropopause Inversion Layer (TIL), detected in 2002

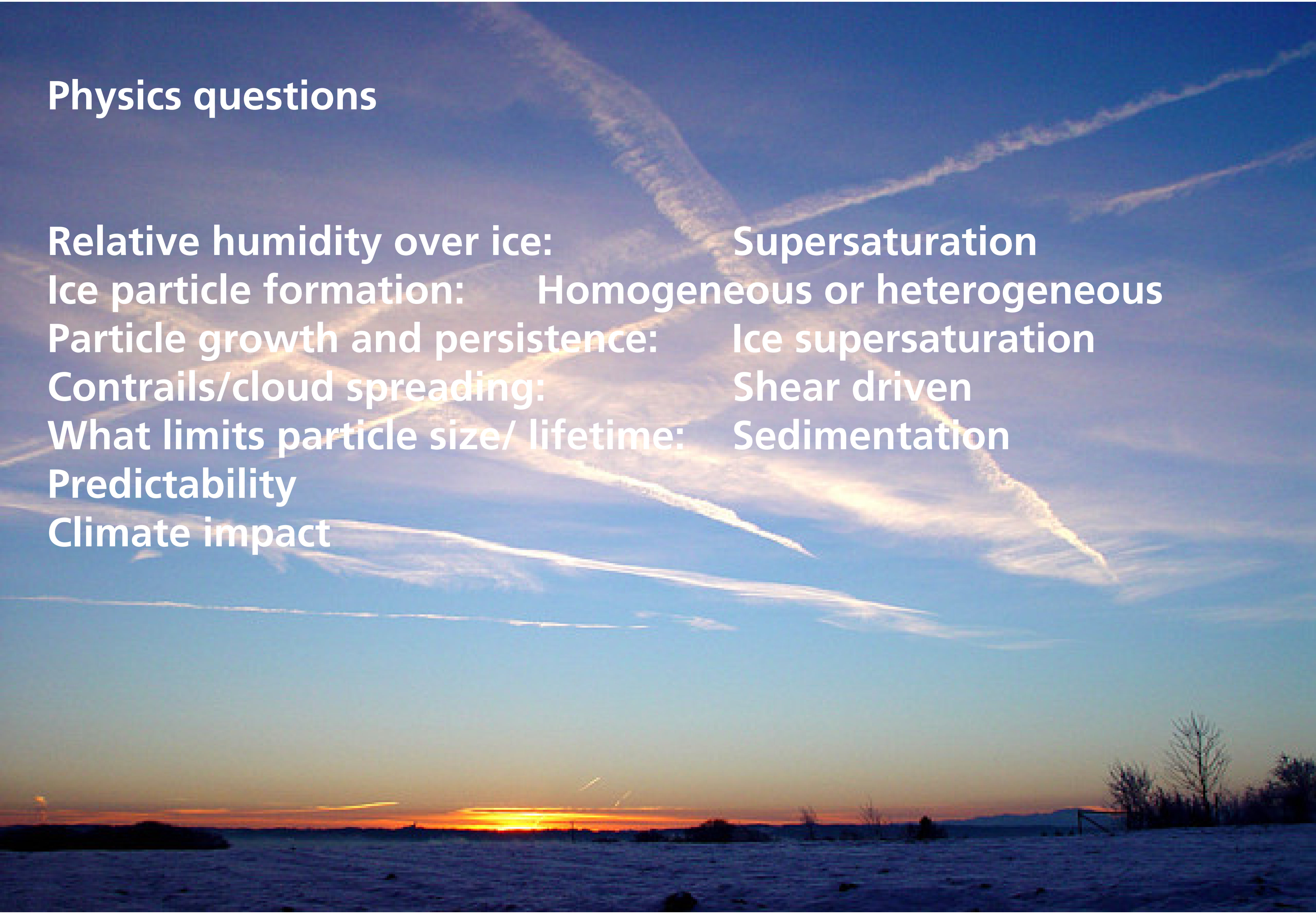
$$N^2 = \frac{g}{\Theta}\frac{\partial \Theta}{\partial z}$$



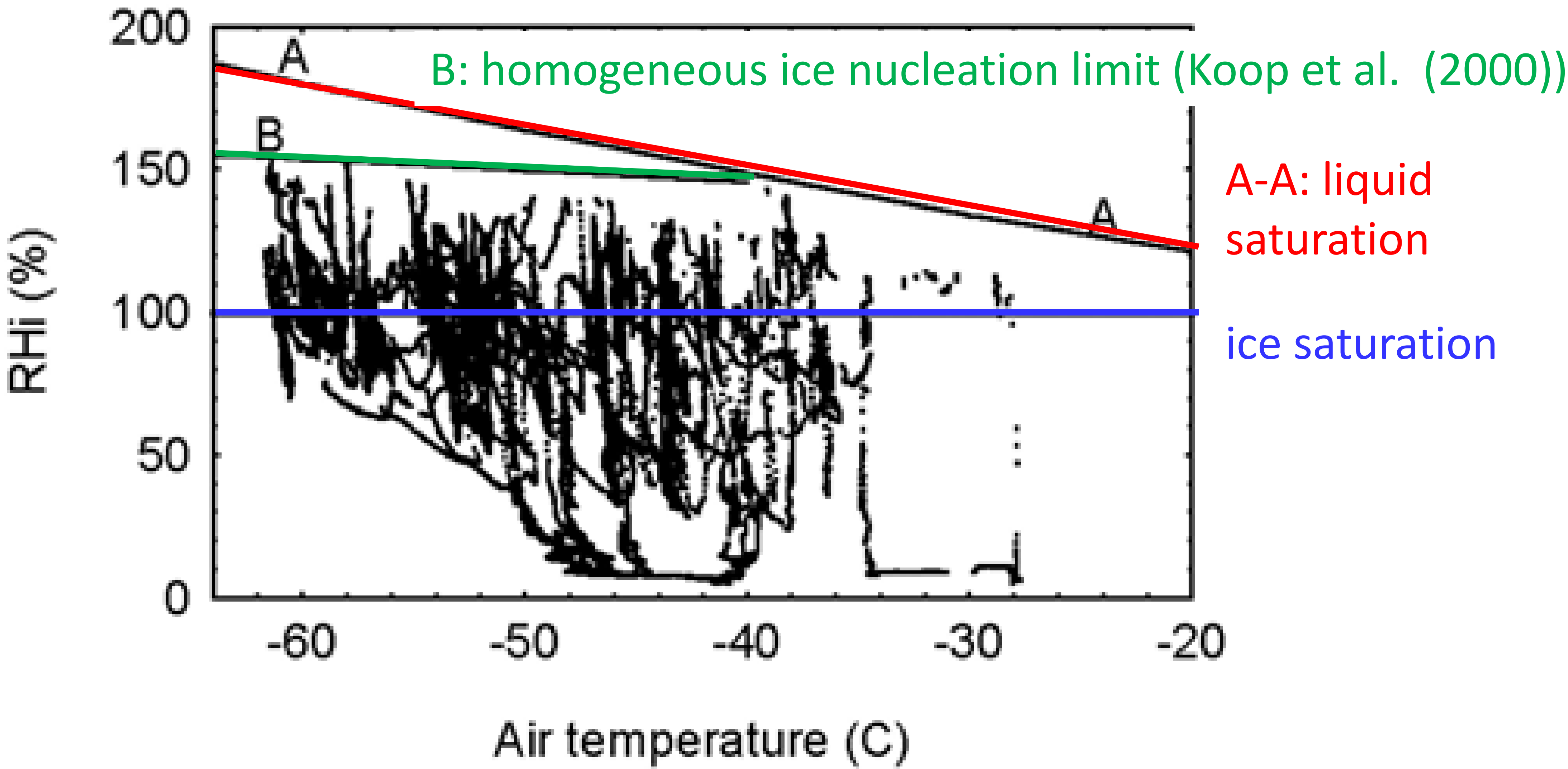
Birner et al. (GRL, 2002; JGR, 2006)

Physics questions

Relative humidity over ice: Supersaturation
Ice particle formation: Homogeneous or heterogeneous
Particle growth and persistence: Ice supersaturation
Contrails/cloud spreading: Shear driven
What limits particle size/ lifetime: Sedimentation
Predictability
Climate impact



Relative humidity over ice: departure from thermodynamics



Measured with frostpoint instrument on DLR-Falcon
Ovarlez et al. (2002)

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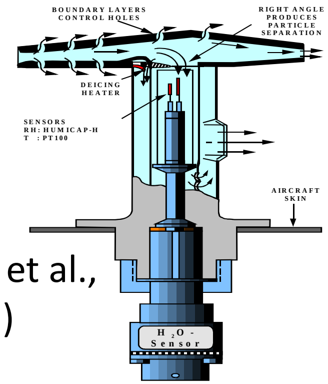
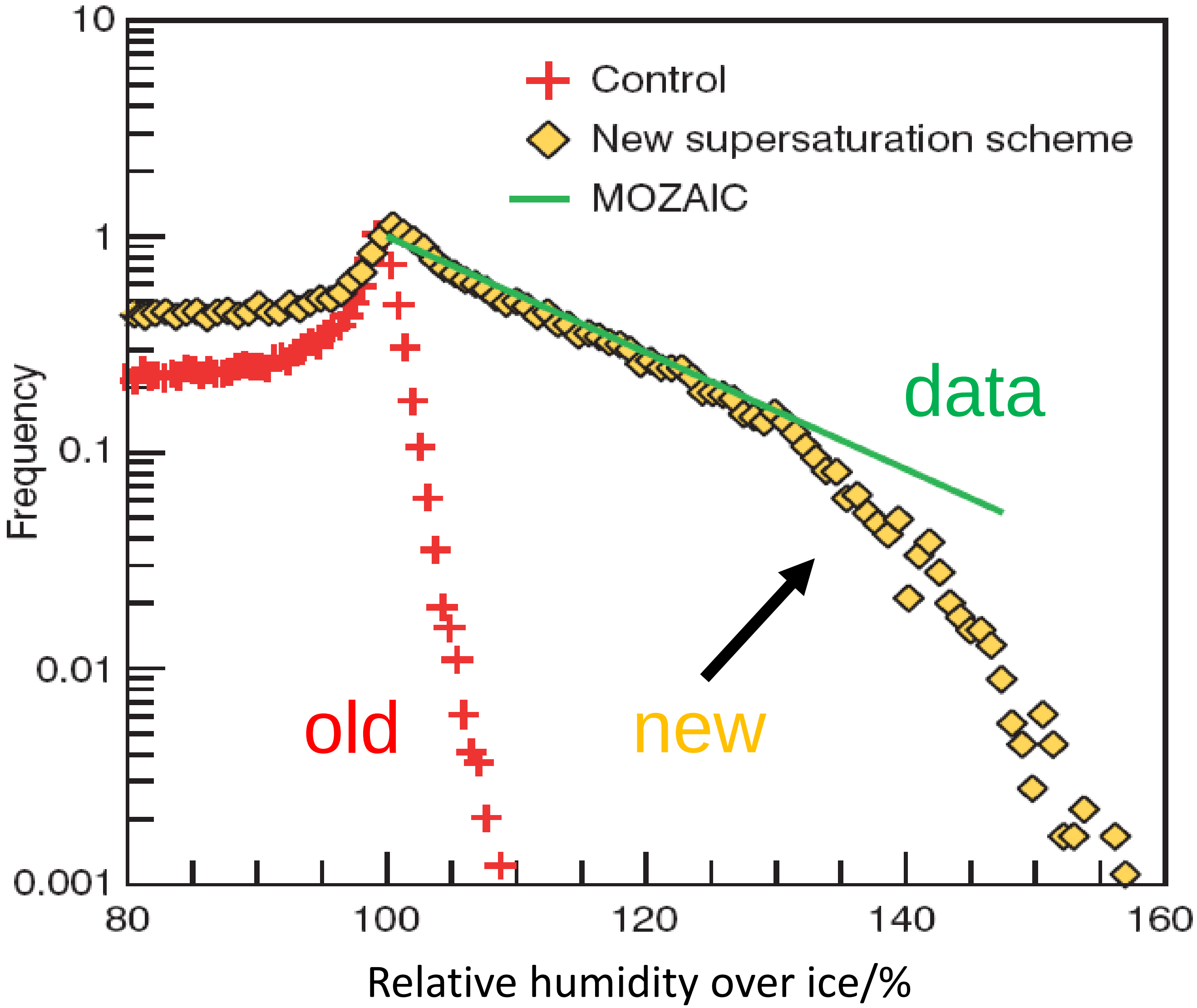
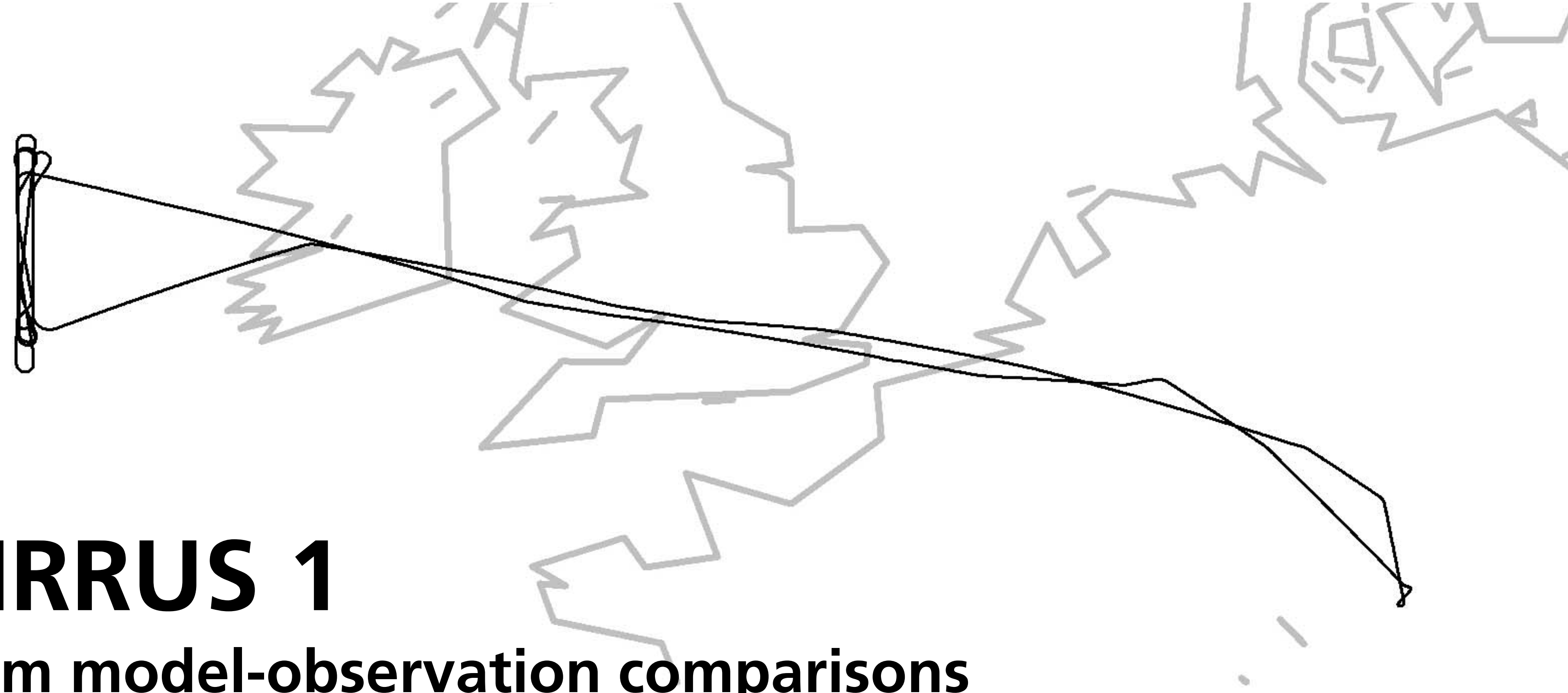
Ice supersaturation in Numerical Weather Prediction scheme of ECMWF: Comparison to MOZAIC humidity measurements



(Smit et al., Jülich)



Tompkins, Gierens, Rädel (2007)

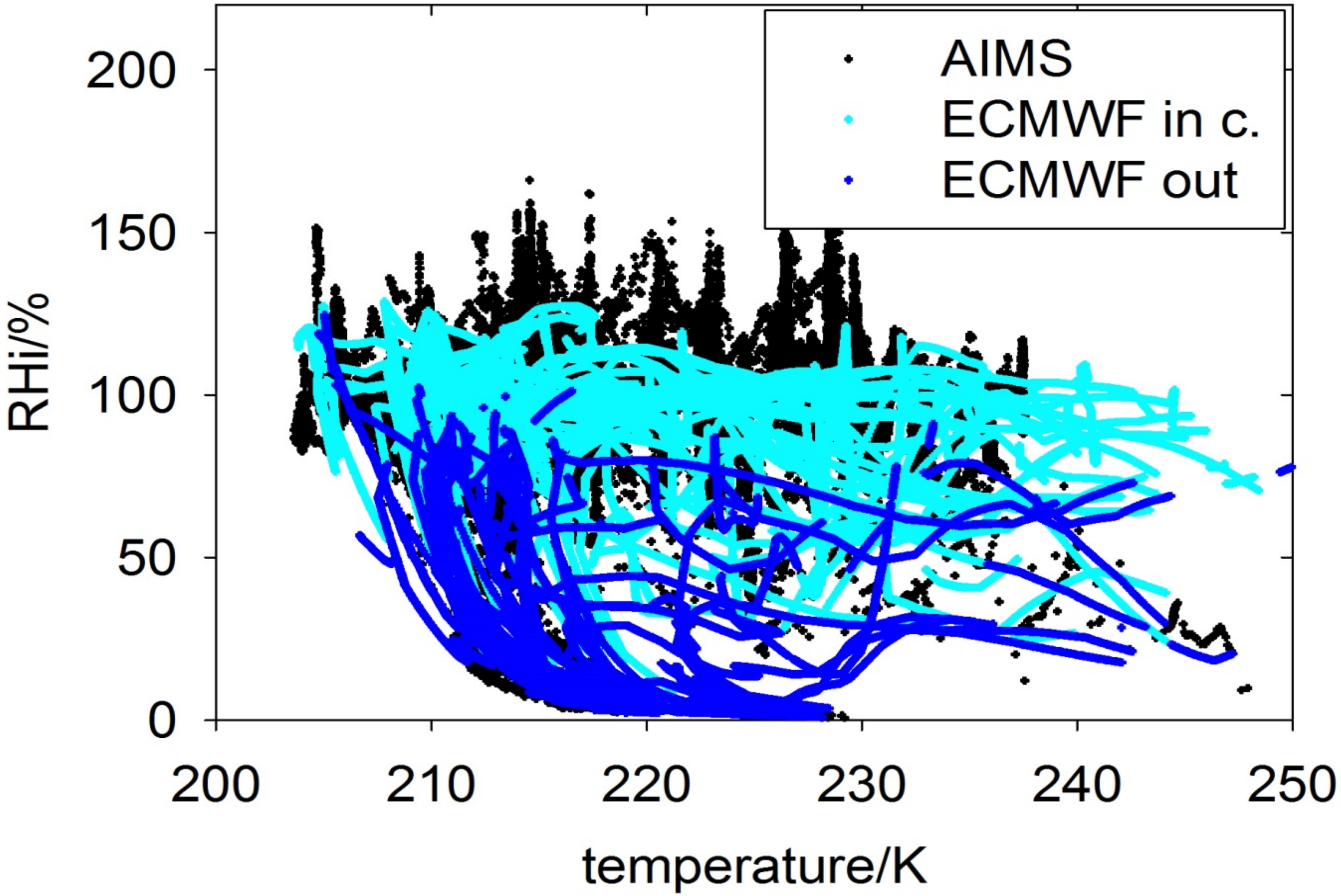


ML-CIRRUS 1

Learn from model-observation comparisons

Voigt, Minikin, Schumann et al., ML-CIRRUS team

Contrails persist in ice supersaturated air masses



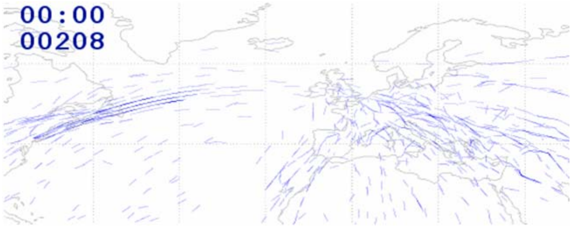
U. Schumann, C. Voigt, S. Kaufmann, A. Giez et al.: ML-CIRRUS

Contrail Prediction with the Contrail Cirrus Simulation and Prediction Model (CoCiP)

Input:

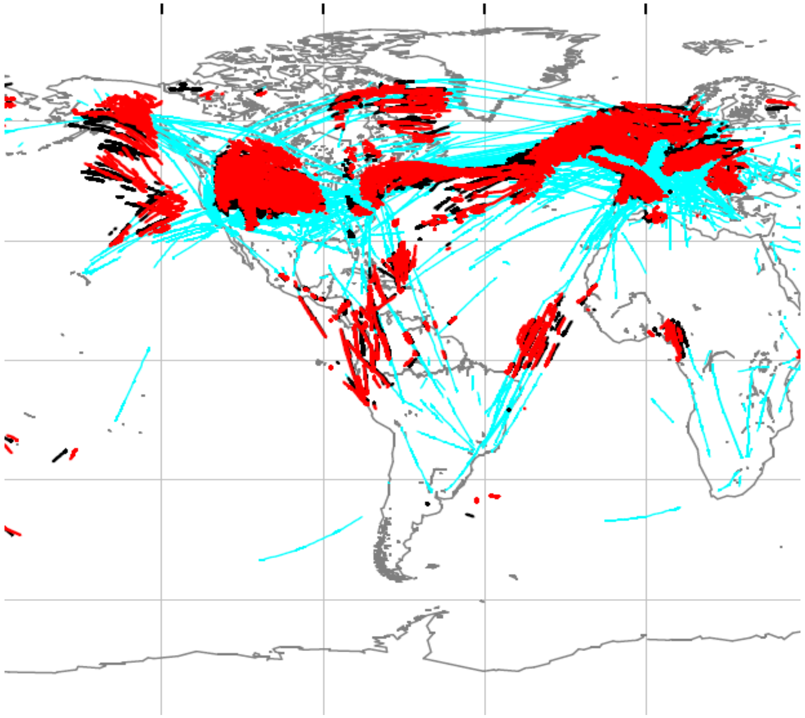
Aircraft (BADA)

Traffic (e.g., FAA 2006)



Meteorology (e.g., ECMWF)

Contrail Cirrus Prediction Tool



- From regional to global
- Comparable to observations

Output:

Contrail,
life cycle,
cover, radiation

Cirrus

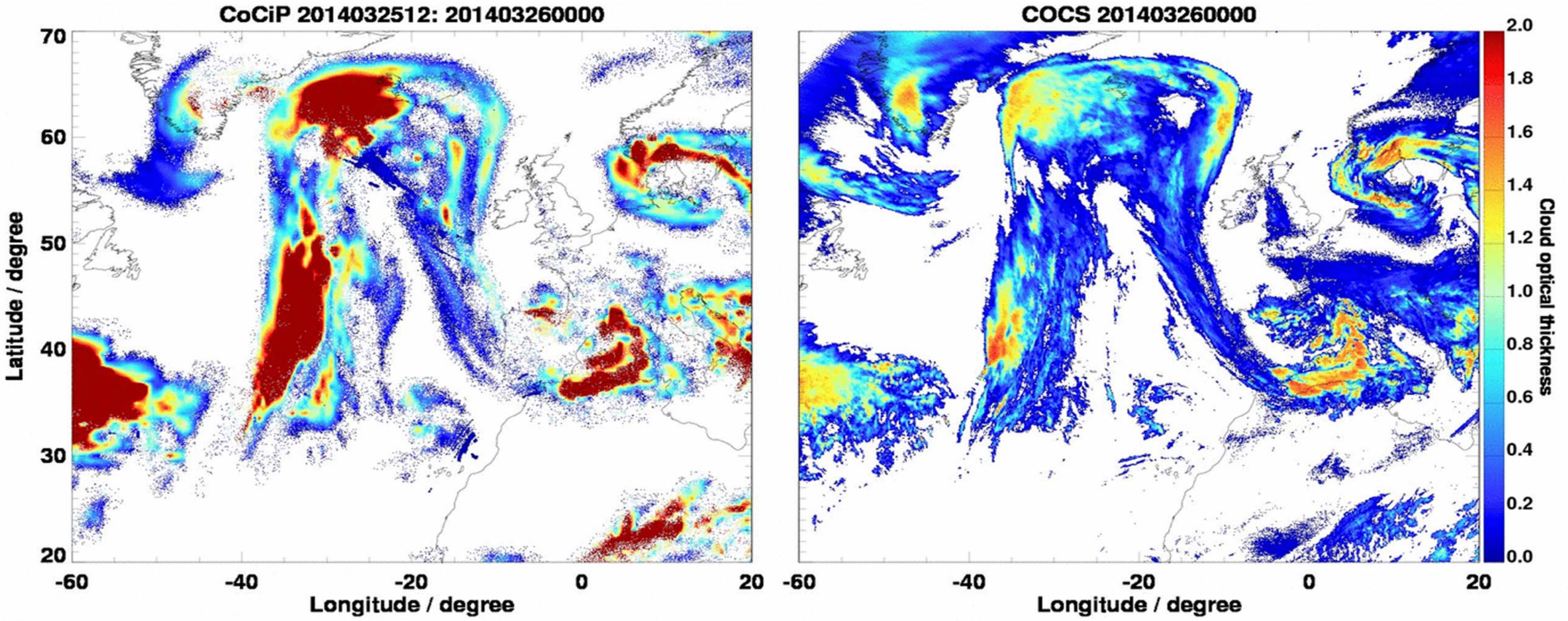
Simulation
(insitu, Lidar, MSG, Modis)

Sensitivity studies

Prediction & Mitigation

(Schumann, 2012)

Predicted and observed optical thickness (Meteosat-COCS)



Optical depth of contrails + cirrus from CoCiP/ECMWF during ML-CIRRUS

(K. Graf and U. Schumann)

Optical depth of thin cirrus derived from METEOSAT SEVIRI IR data using the COCS algorithm (Kox, 2014),

Data processed and plotted by L. Bugliaro, 2015

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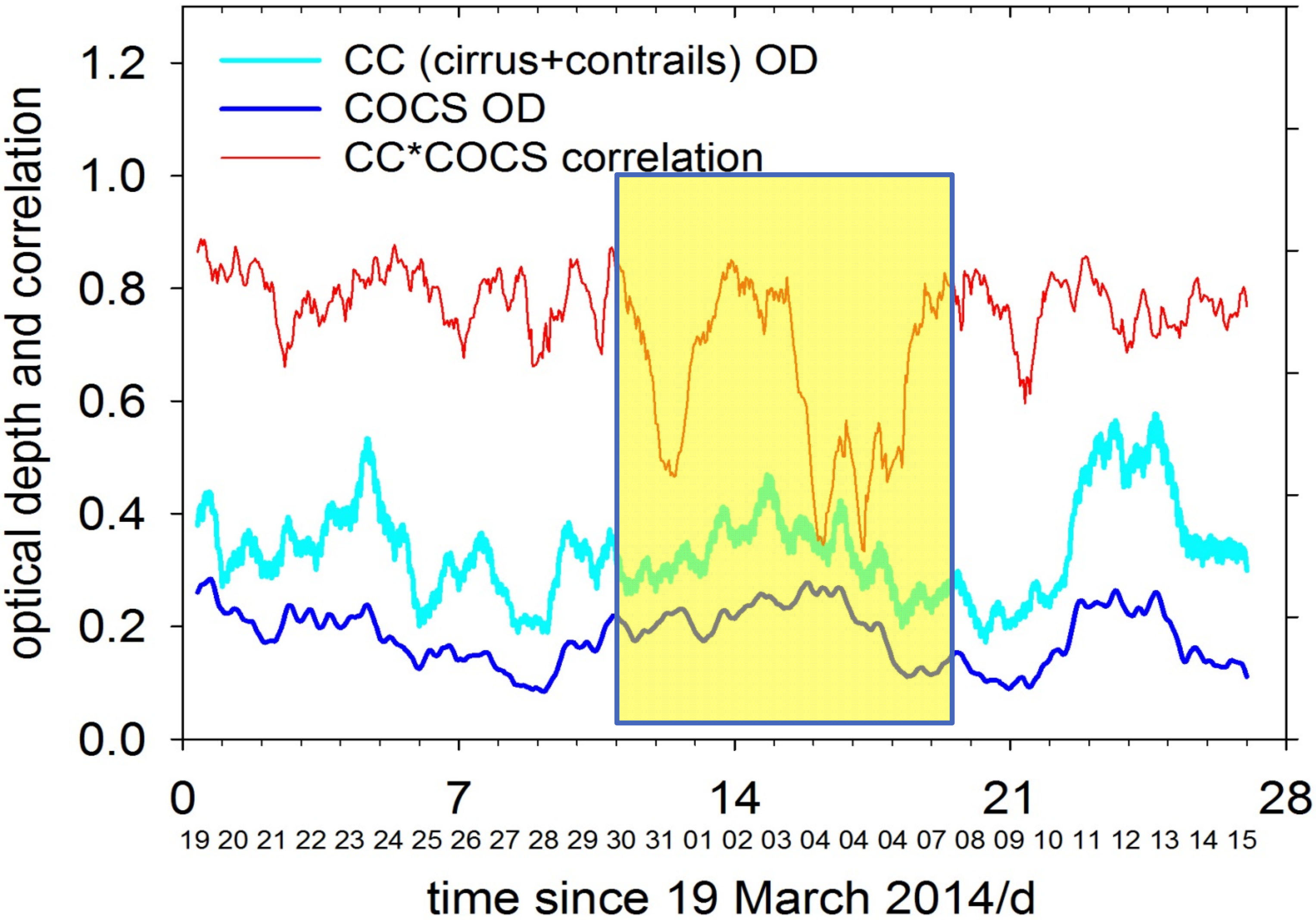
Correlation between forecast and observations

dust period
29.3. -7.4.



correlation: 70-90 % outside dust period

Heterogeneous nucleation on dust not yet modelled in ECMWF IFS model

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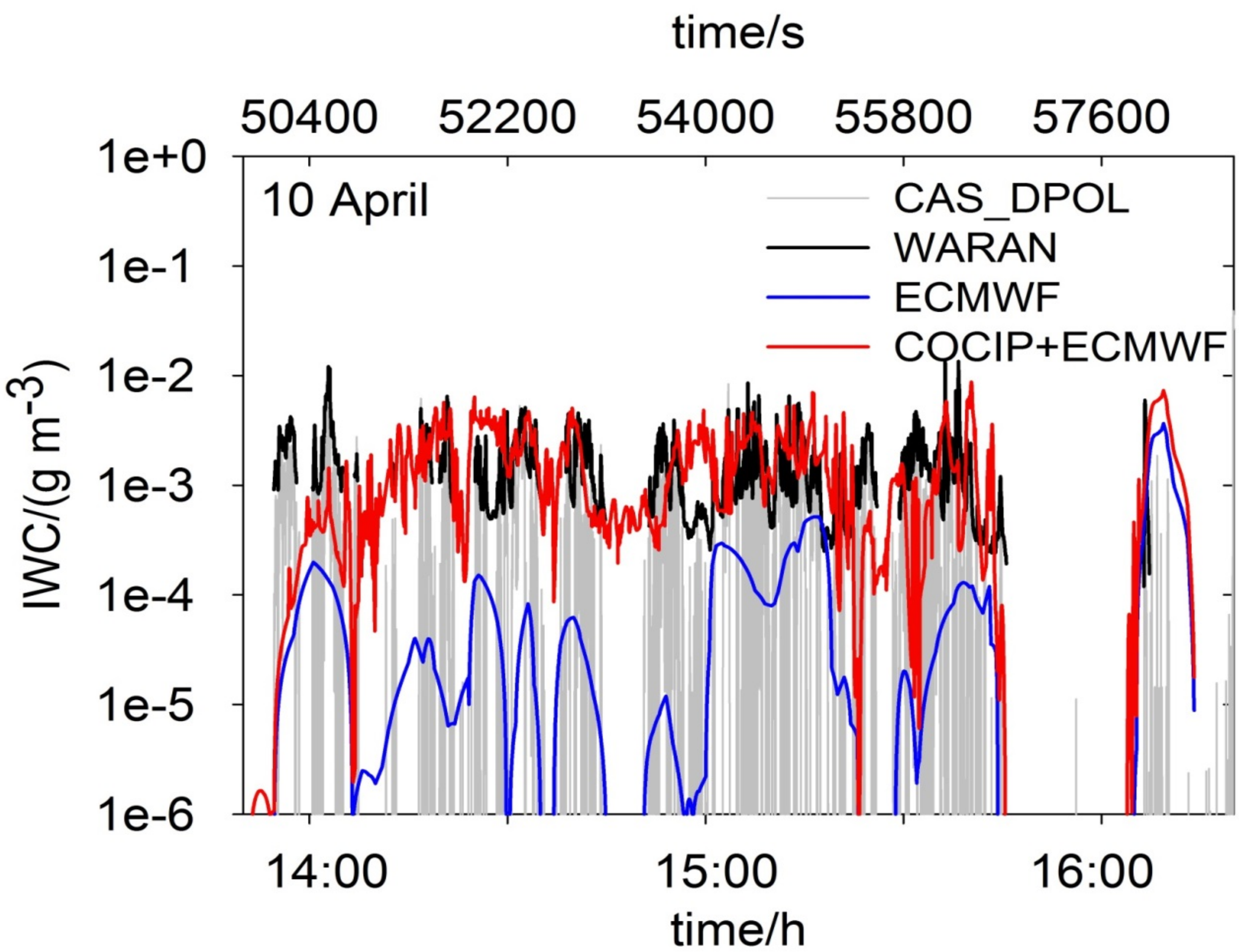
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS.

Here: Ice water content for 10 April 2014



preliminary data, Schumann, Voigt, Jurkat, êt al.: ML-CIRRUS

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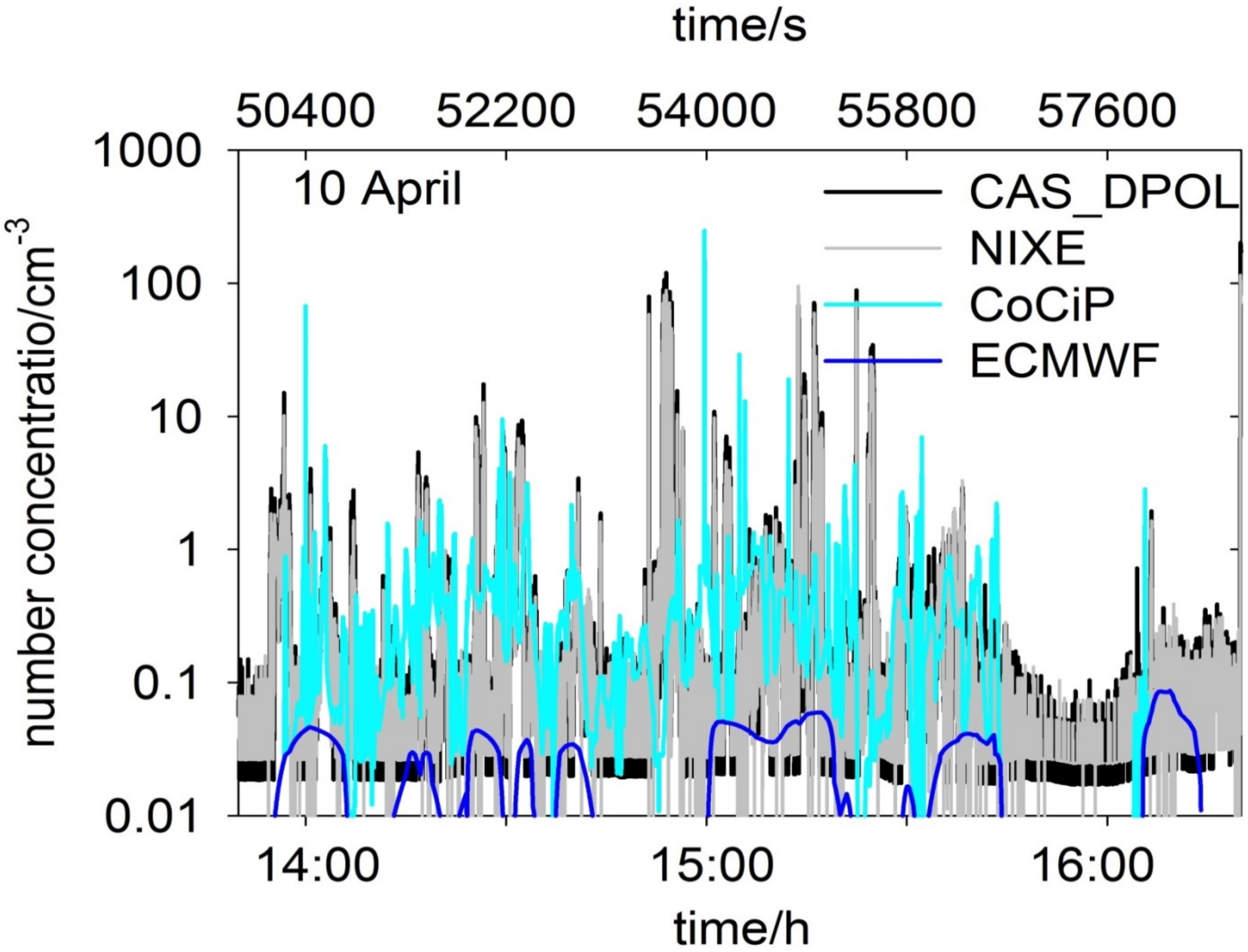
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS.

Here: Ice particle number concentration for 10 April 2014



preliminary data, Schumann, Voigt, Jurkat, Krämer et al.: ML-CIRRUS

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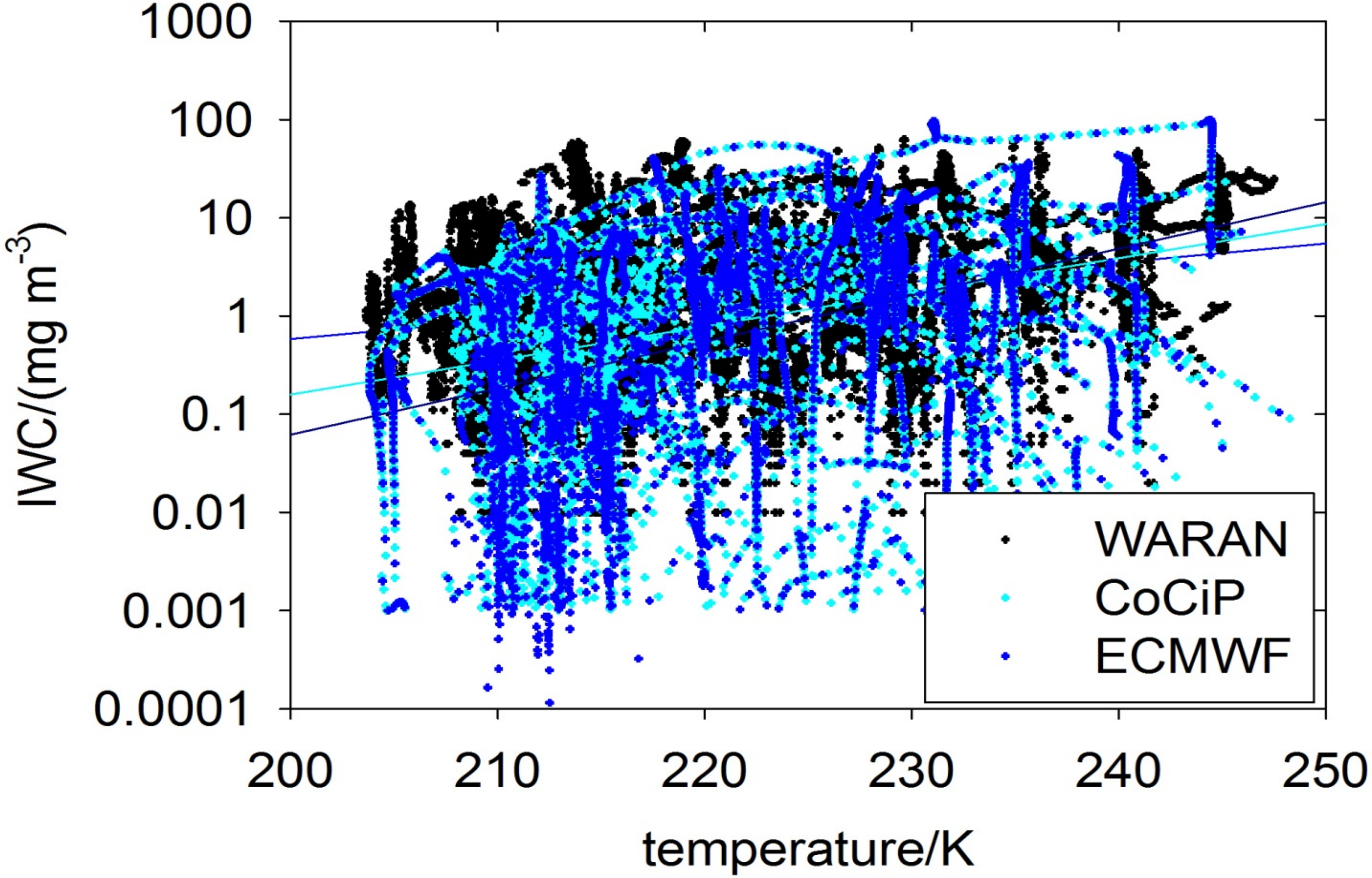
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS. Here IWC for all ML-CIRRUS flights



preliminary data, Schlage, Voigt, Graf, Schumann et al.: ML-CIRRUS

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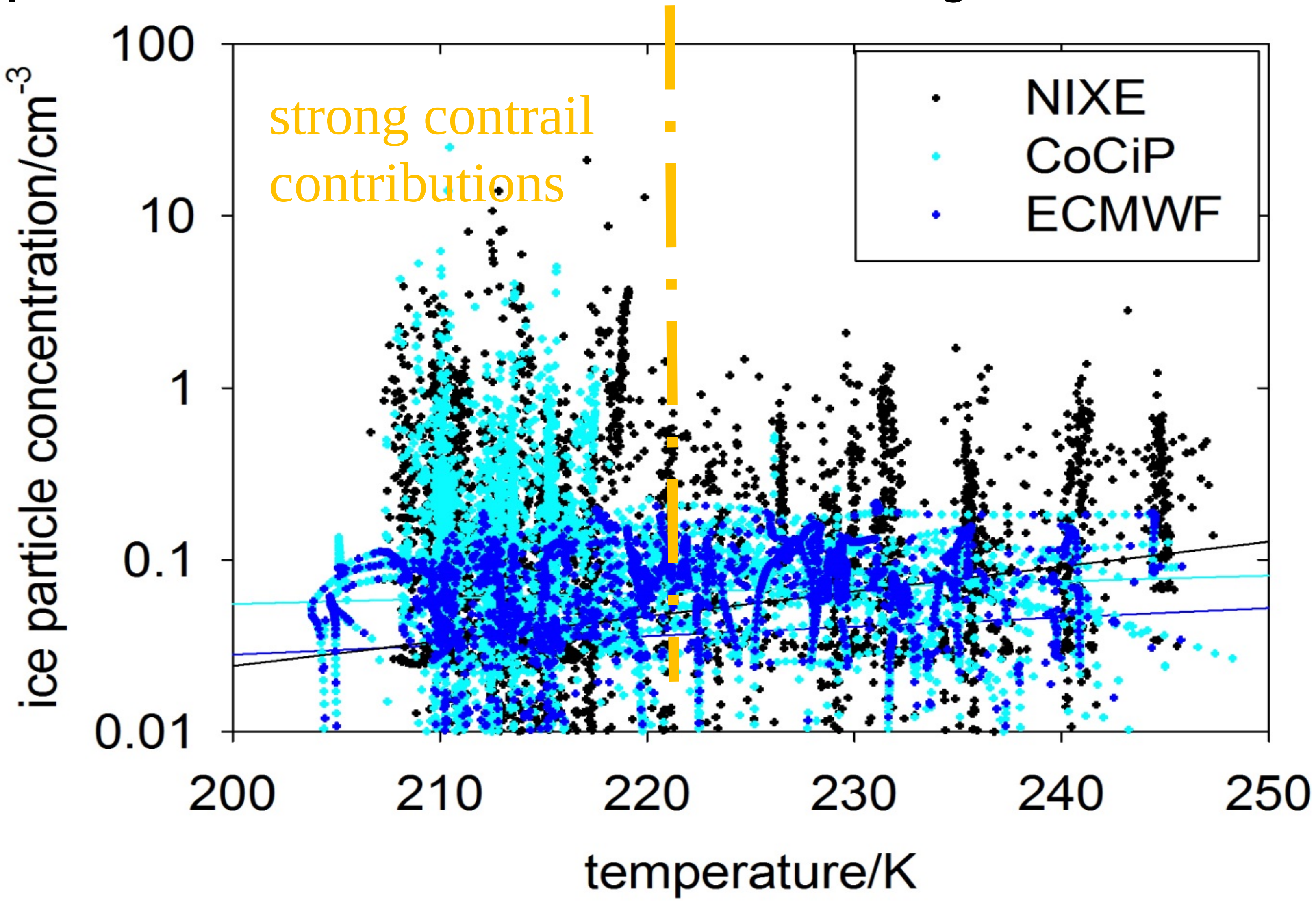
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS.

Here: Ice particle concentration for all ML-CIRRUS flights



preliminary data, Krämer, Schumann, Voigt et al.: ML-CIRRUS

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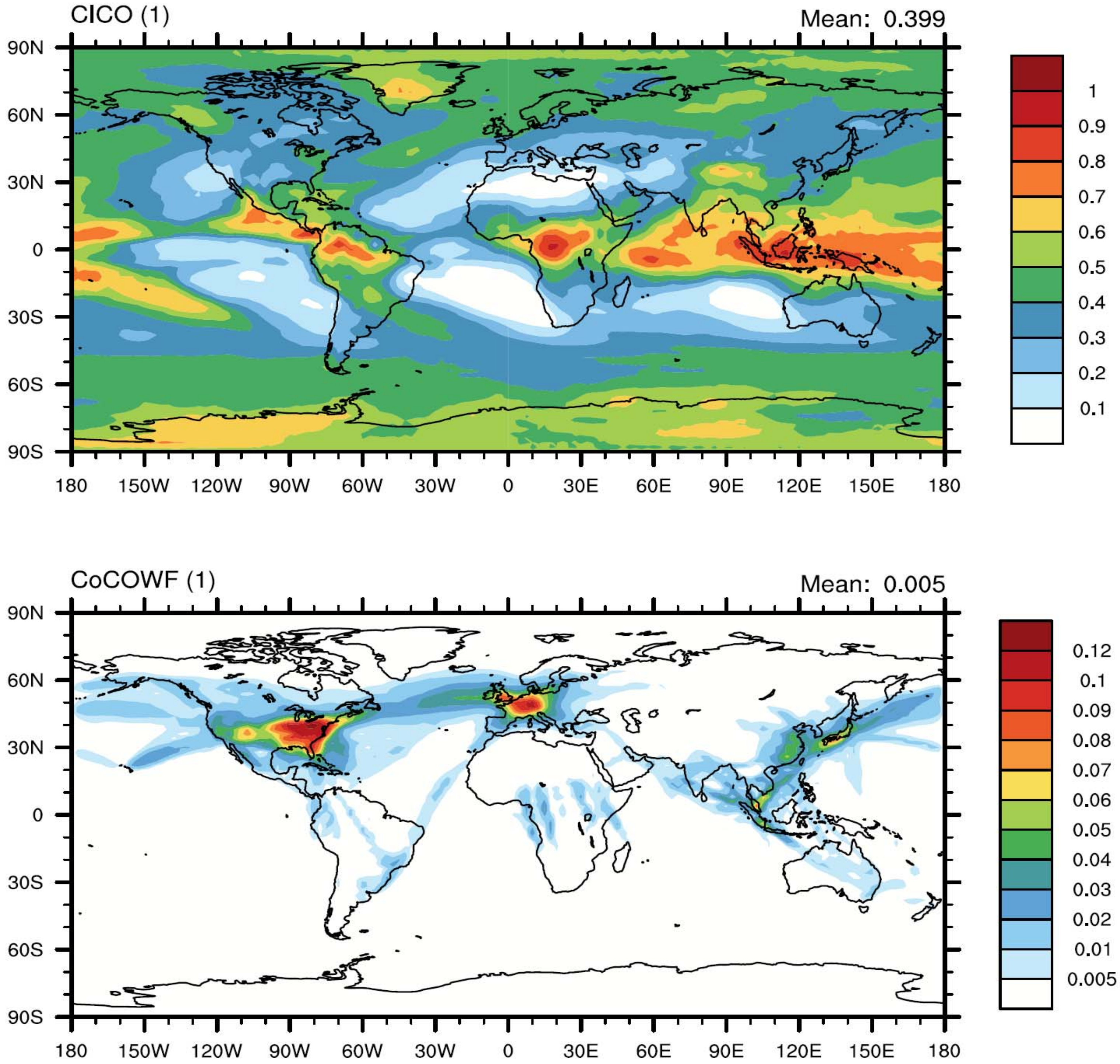
Global mean cirrus cover

and

cover of contrails (τ>0.1)



Schumann, Penner, Chen, Zhou, Graf, (ACPD, 2015)

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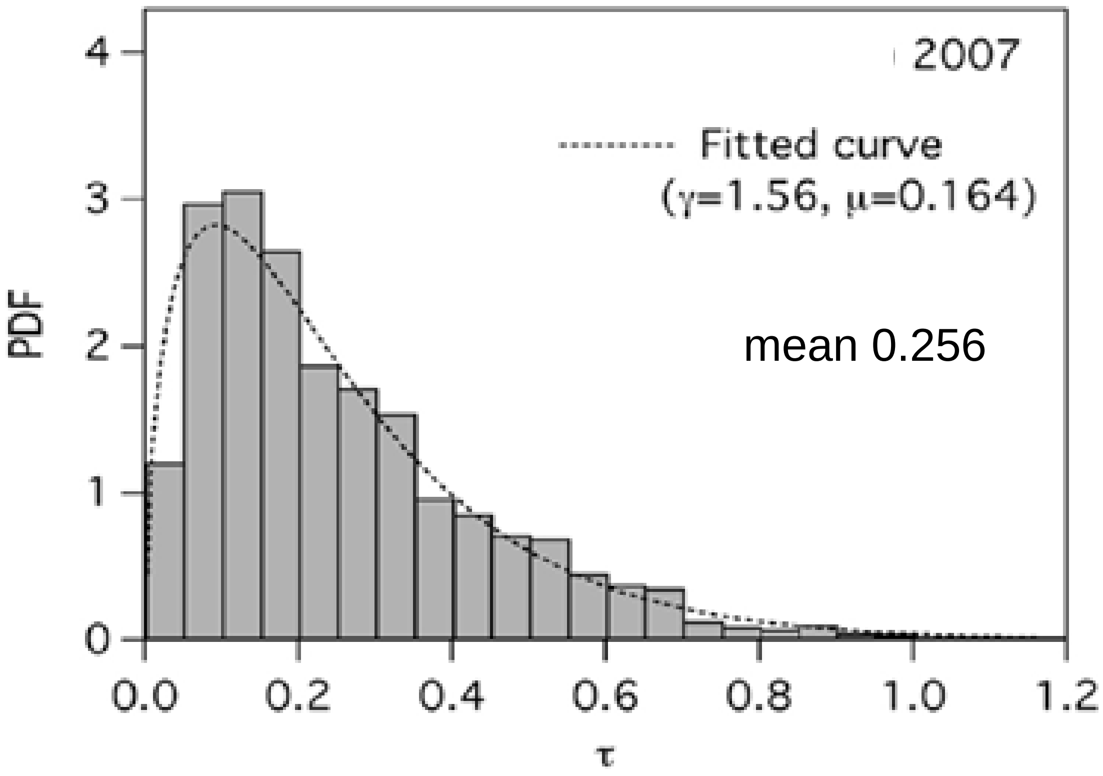
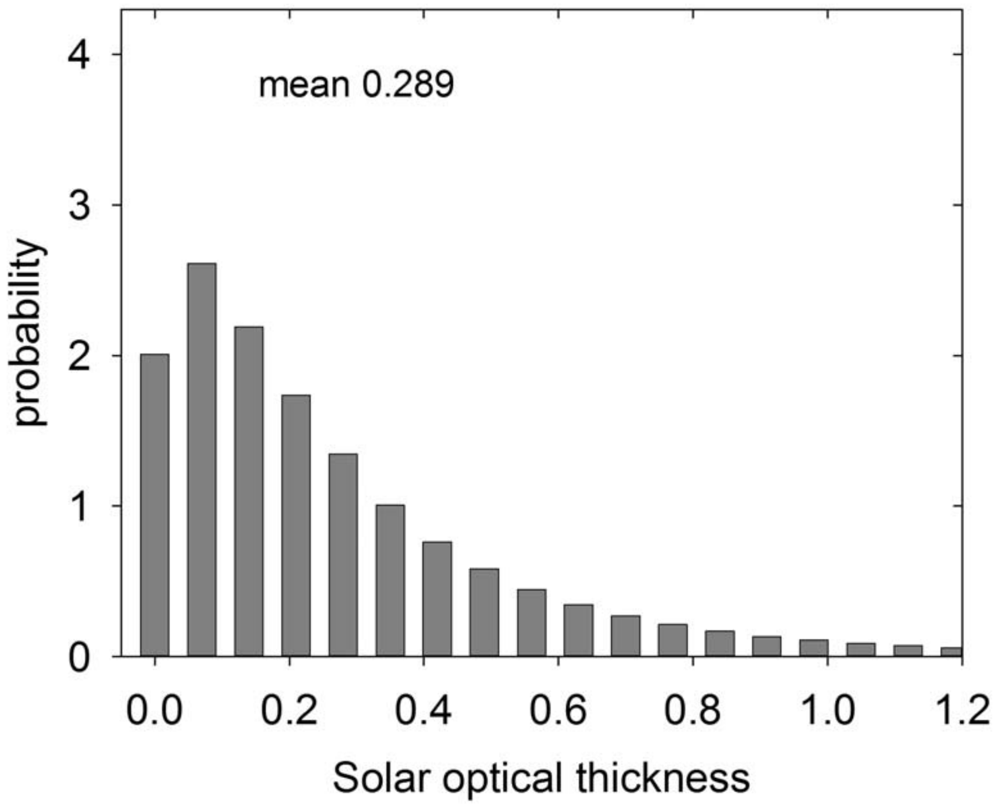
Pdf of contrail solar optical depth occurrence
from MODIS-CALIPSO Observations and CoCiP-CAM Model



(Iwabuchi et al., 2012, JGR)



(Schumann, Penner et al., ACPD, 2015)

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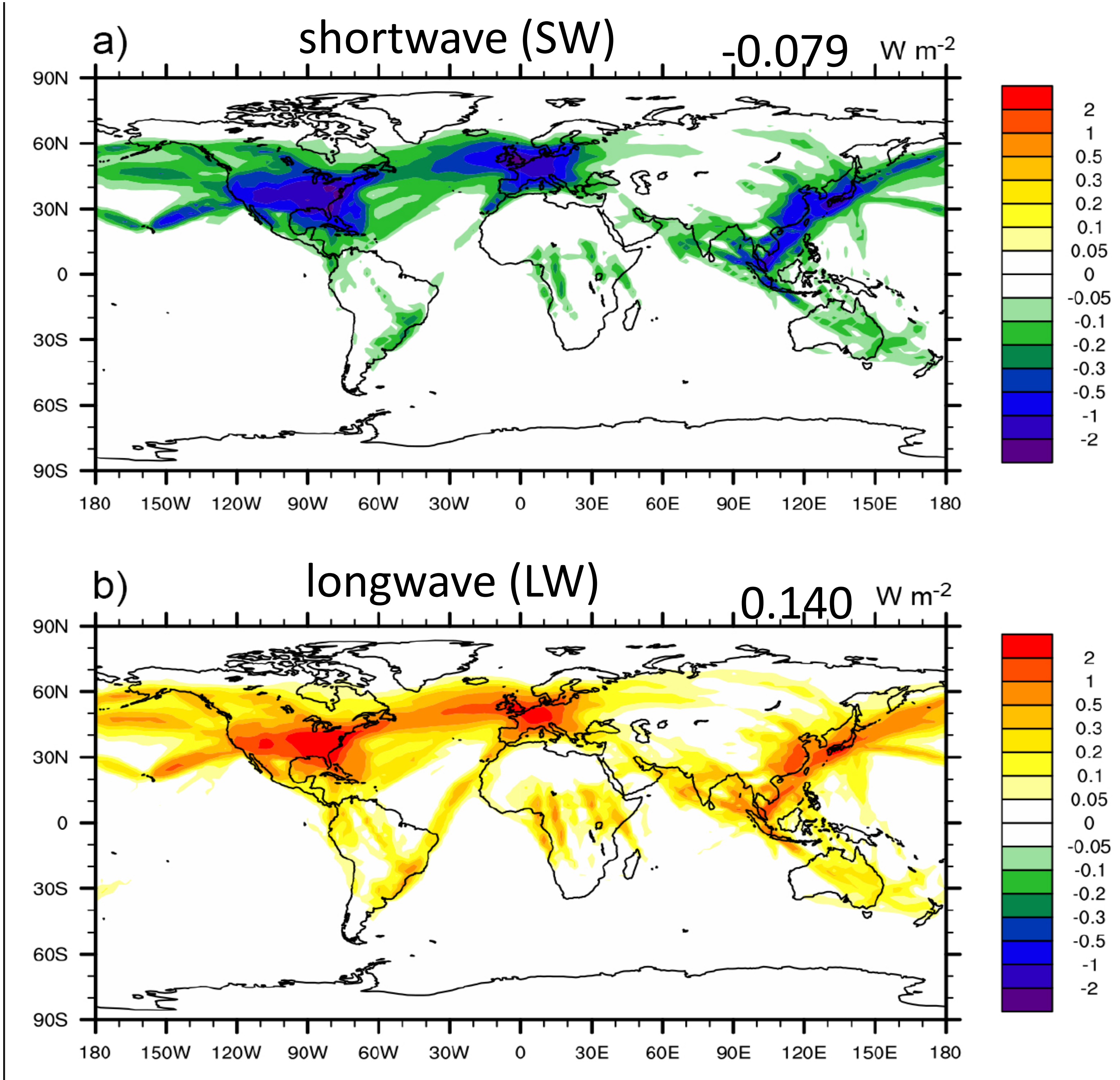
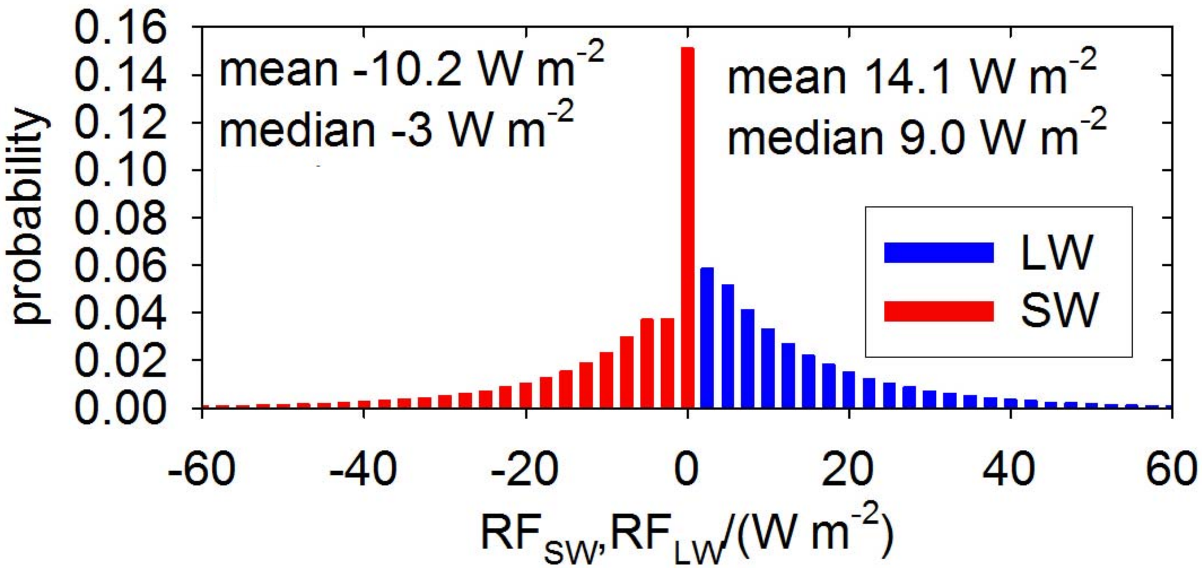
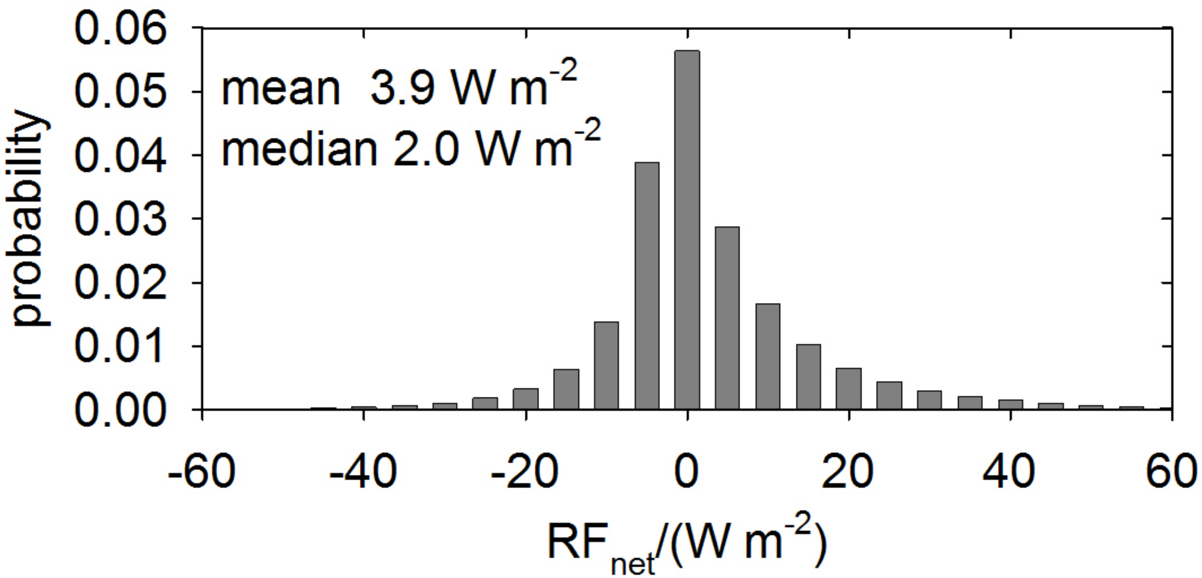
Annual mean radiative forcing by contrails



Schumann, Penner, Chen, Zhou, Graf, (ACPD, 2015)

Local RF per unit contrail area: contrails may cool or warm





Schumann, Penner, Chen, Zhou, Graf, (ACPD, 2015)

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Green Aviation: what can be done?

ETS Aviation. http://www.etsaviation.com/documents/ETS%20-%20corporate%20brochure%202011.pdf

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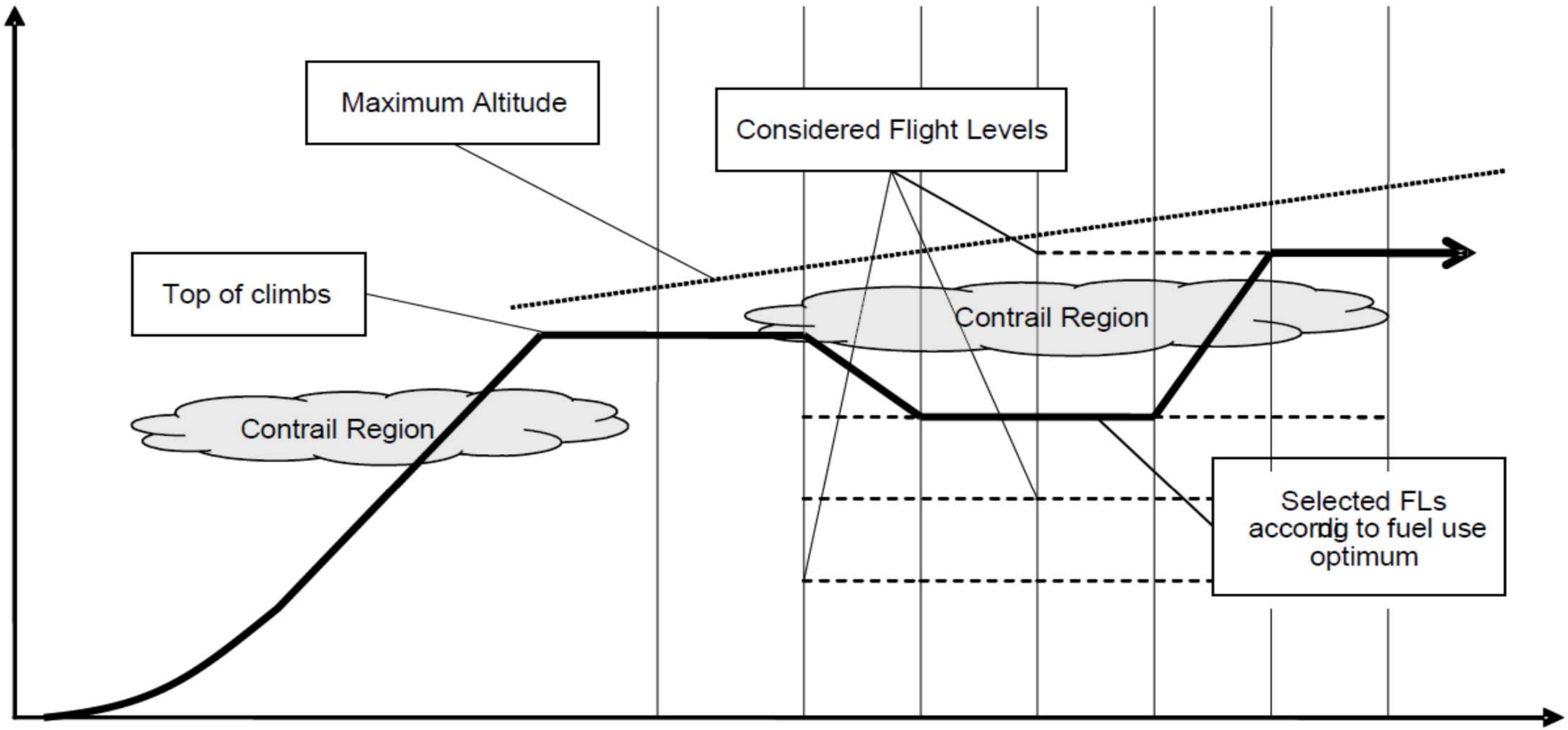
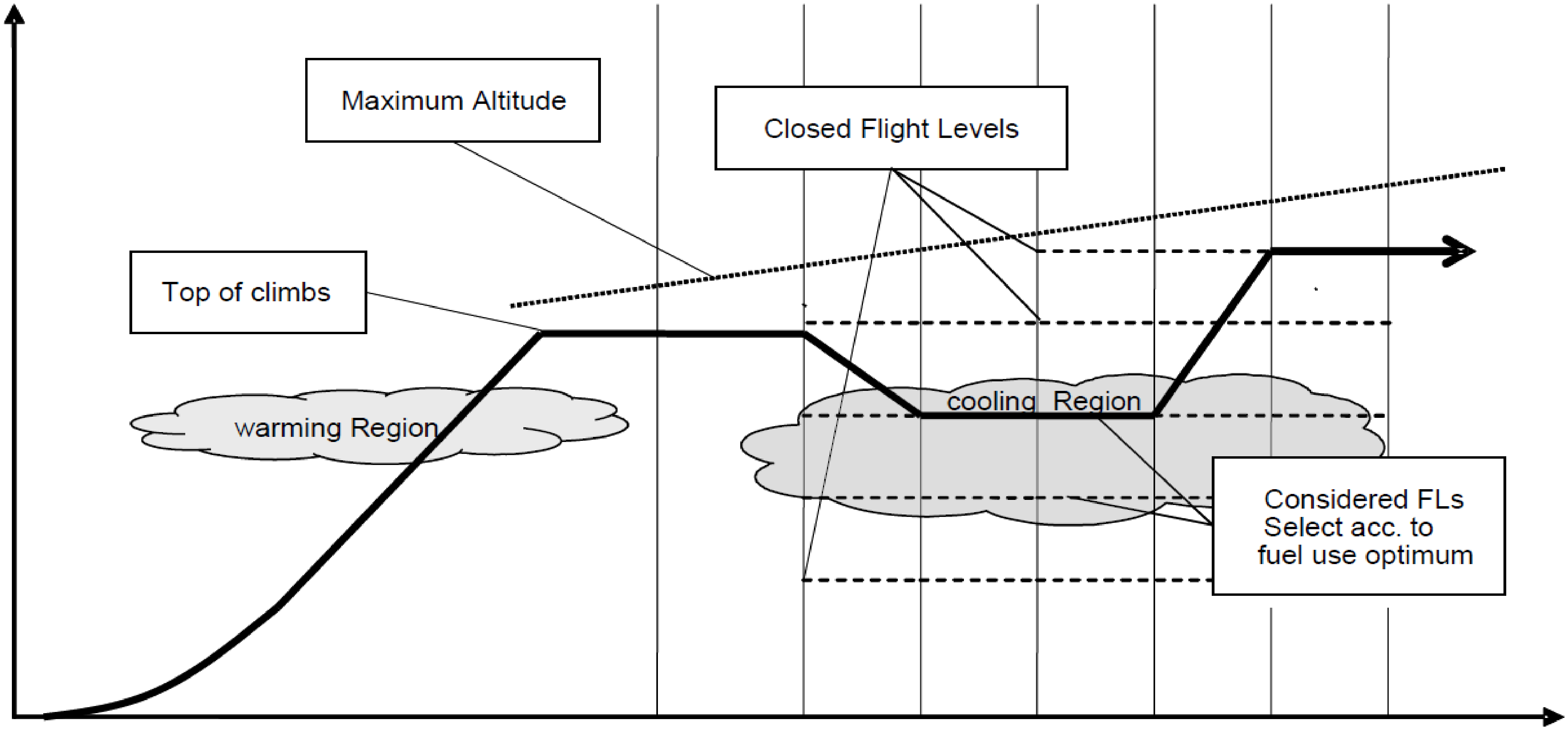
Route optimisation: avoid contrails



Mannstein, Meilinger et al. (2010), referred to in Mannstein and Schumann (patent, 2015)

Better: avoid warming contrails but enforce cooling contrails



Mannstein, Meilinger et al. (2010), referred to in Mannstein and Schumann (patent, 2015)

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Conclusions

Cirrus clouds are thin ice clouds affecting Earth' albedo and greenhouse effect, and hence climate

Contrails are reproducible prototypes of cirrus clouds

Investigations of contrail formation led to important general insight into the atmosphere system

Examples: Brewer-Dobson circulation, detection of ice supersaturation, homogeneous and heterogeneous ice particle formation.

Understanding requires model-observation comparisons

Contrail Cirrus is predictable to some quantifiable degree

Contrails cool or warm - this opens mitigation options

Outlook

Improve prediction reliability (e.g. soot and dust aerosols)
Include other emissions (NOx, SO_2, etc.)
Include other traffic modes (ships, car traffic)
Support sustainable development by better science
Science does not exclude applications

(Foto from Falcon: ships in the Strait of Malacca - Courtesy Hans Schlager)

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